Wide-Bandwidth Near-Infrared Avalanche Photodiode Photoreceiver

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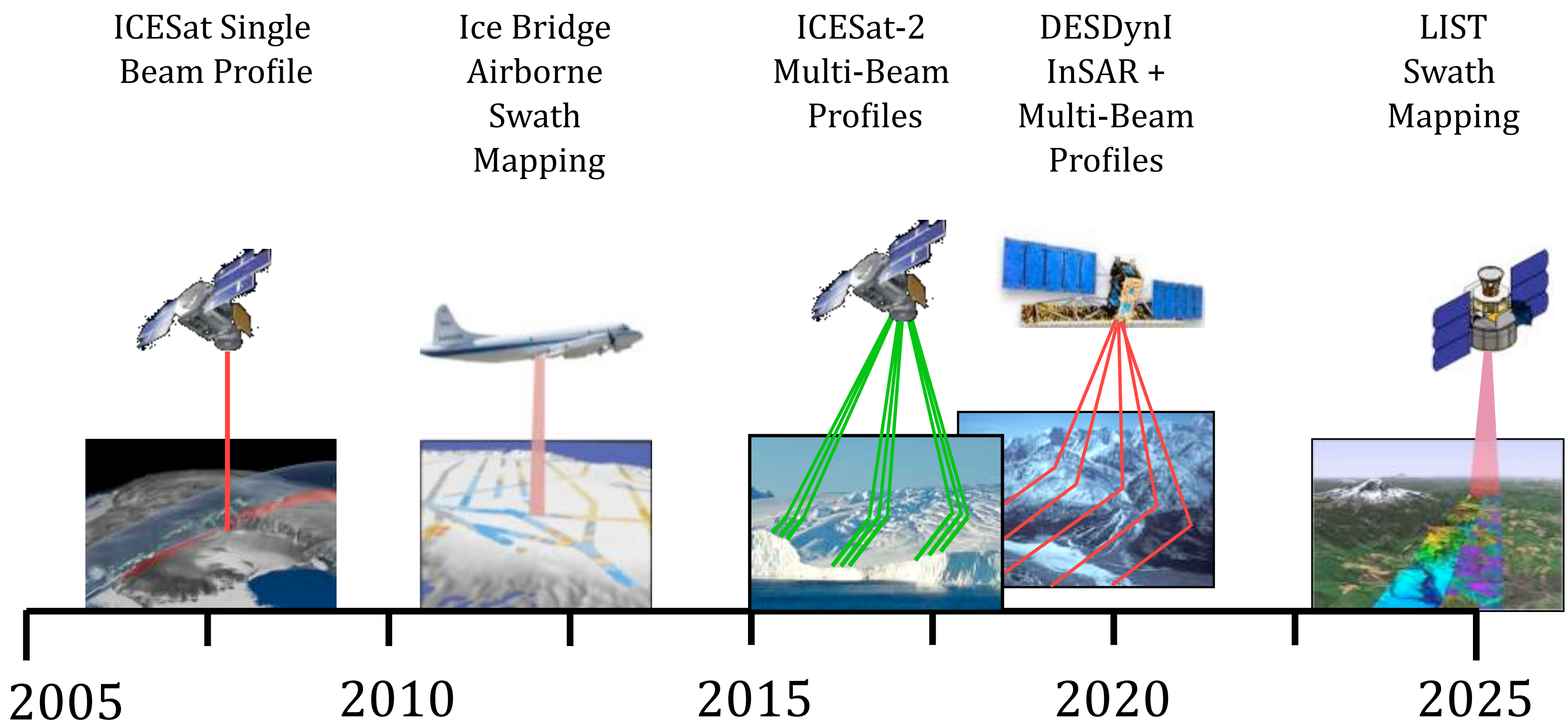
Outline

- NASA lidars
- Receiver Requirements
- Gen.1 photoreceiver design and performance
- Gen. 2 design and receiver development
  - I^2E low excess noise APD design
- Summary

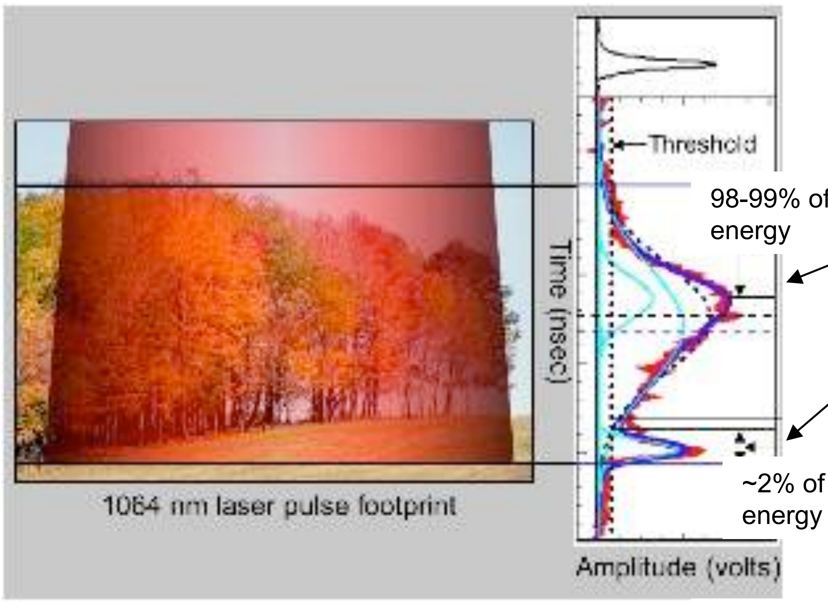
Space Borne Laser Altimeter Evolution ICESat/GLAS to LIST



NRC Earth Science Decadal Survey Missions

Requirement to detect the weakest signal drives the lidar design
(courtesy of J.Abshire)

A sample ICESat/GLAS Echo Waveform from tree(s)



Echo pulse waveform
(backscattered laser power vs time)

Echo pulse from Tree canopy

Echo pulse from ground under trees
Energy proportional to canopy opening faction
For LIST, the opening fraction is ~2%

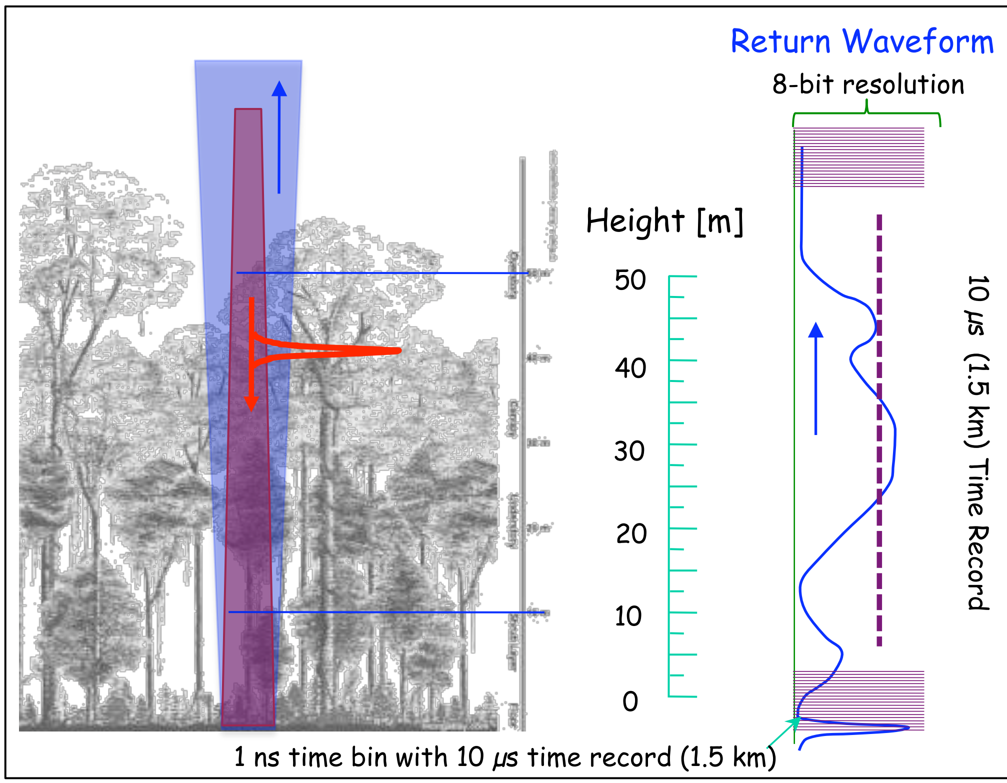
- *GLAS acquires waveforms from vegetated terrain in a ~ 70 m diameter laser footprint*
- *Waveforms show height distribution of backscattered light reflected from canopy surfaces and underlying ground*

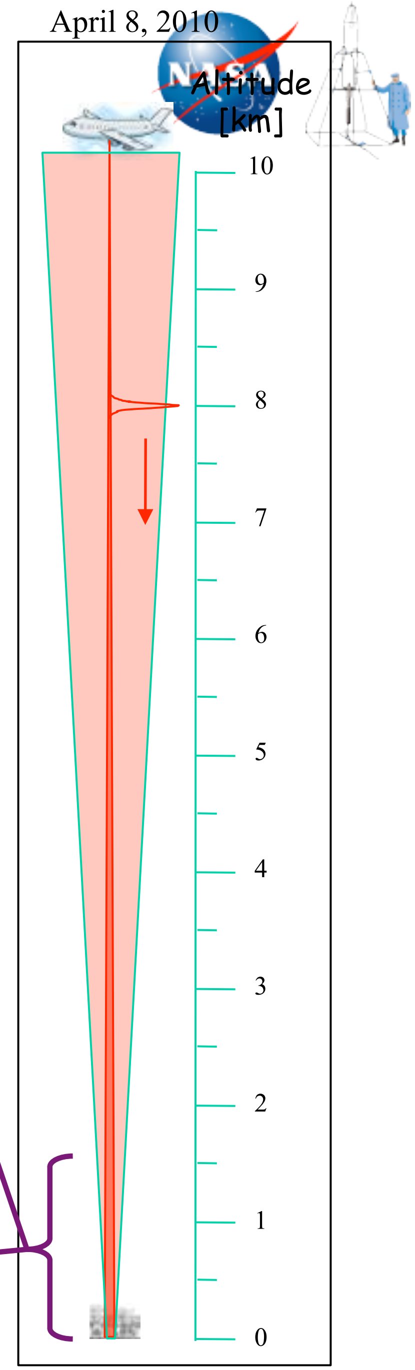
Energy in ground echo is ~2% of that from tree tops

- Is weakest signal the altimeter receiver has to detect
- Energy scales with sub-canopy surface reflectivity
- Must reliably detect signal in presence of noise
  - (detected solar background rate)
- Need at least several detected photons/pixel

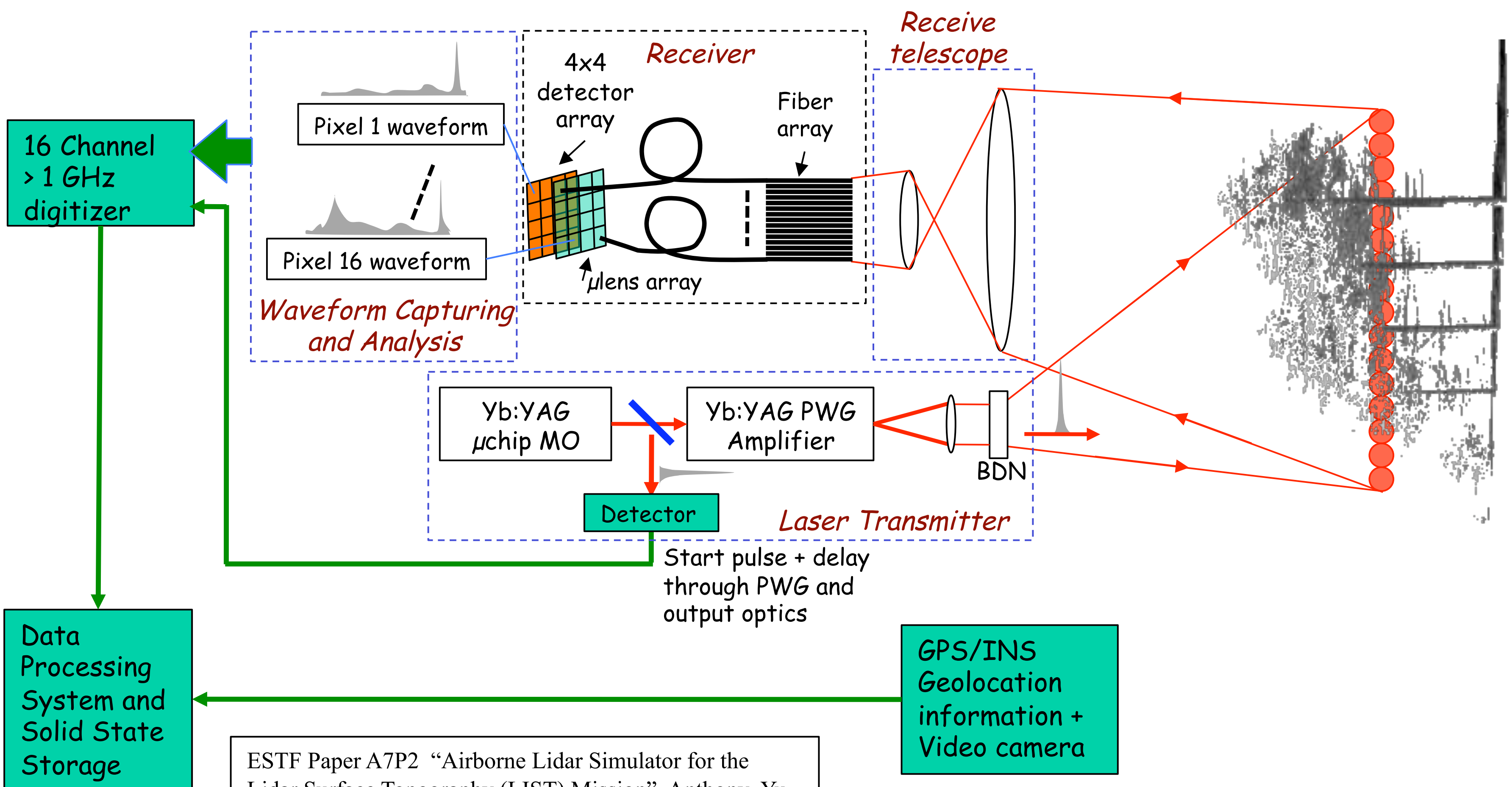
Lidar analog waveform processing

	Analog ICESat-2 approach	Swathmap IIP and LIST
Laser transmitter pulsewidth (ns)	6 ns	< 1 ns
Optical receiver/ detector BW	160 MHz	1 GHz





ESTO-IIP (Yu-PI)
Airborne Instrument Concept



ESTF Paper A7P2 "Airborne Lidar Simulator for the Lidar Surface Topography (LIST) Mission" Anthony Yu

ESTF Paper A7P3 "The Slope Imaging Multi-polarization Photon-counting Lidar: an Advanced Technology Airborne Laser Altimeter" David Harding

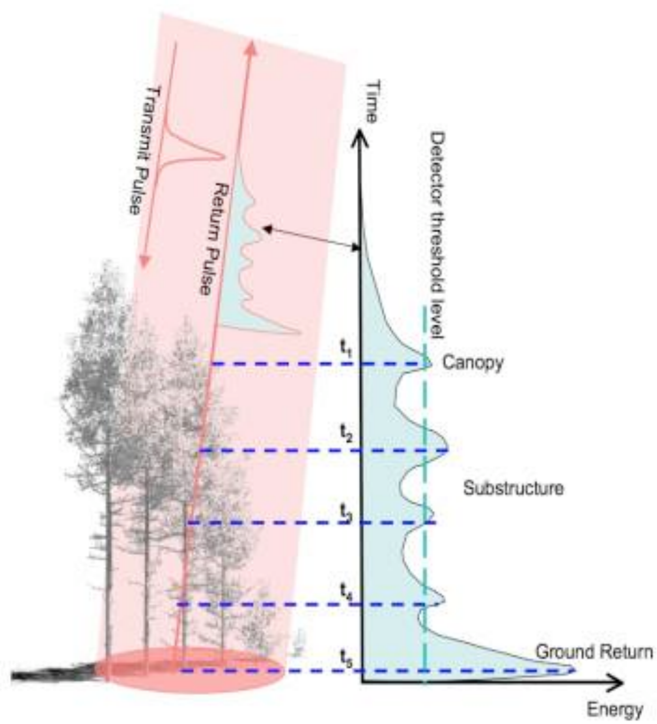
BDN-Beam Dividing Network

Receiver Requirements

Goal:

Generation 1: 1.06µm APD receivers with 200 µm aperture, sensitivity < 100 fW/Hz$^{1/2}$ @ a bandwidth of 140 MHz

Generation 2: 1.06µm APD receivers with sensitivity < 300 fW/Hz$^{1/2}$ @ bandwidth of 1GHz



Lidar received pulse width variance

$$Var(T_R) = \frac{T_T^2}{\langle N \rangle} + \left(\frac{1}{\langle N \rangle} + \frac{1}{K_S}\right)\frac{4Var(\xi(surf\,ace))}{c^2\cos^2\phi_S} + \left(\frac{1}{\langle N \rangle} + \frac{1}{2K_S}\right)\frac{4z^2}{c^2\cos^2\phi_S}\left(\tan^4\theta_T + \tan^2\theta_T\tan^2\phi_S\right)$$

$$K_S = \pi A_R\left(\frac{2\tan\theta_T}{\lambda_0}\right)^2$$

"Target signatures for laser altimeters: an analysis" C. S. Gardner APPLIED OPTICS /Vol. 21, No. 3 448 1 February 1982

$\langle N \rangle$ is the expected number of detected signal photons per received pulse

x_S is the surface profile variation (meters)

q_T is the laser beam divergence angle halfwidth at the 1/(e^2) point. (radians)

A_R is the area of the recei,ver aperture. (square meters)

l_0 is the laser wavelength (meters)

f_S is the surface slope angle (radians)

z is the altitude (meters)

c is the speed of light (meters/second)

T_R is the received pulse width (seconds)

T_T is the transmitted pulse width (seconds)

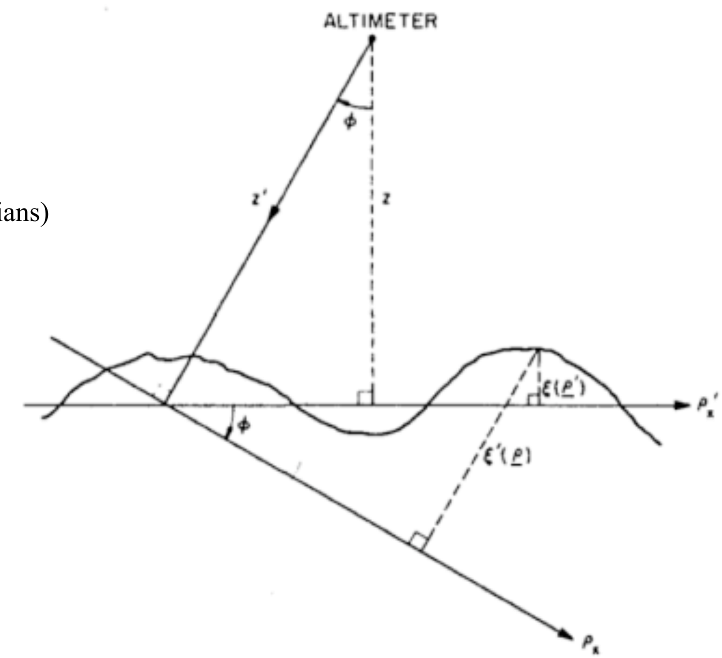


Fig. 2. Geometry of the laser altimeter and ground target for non-normal incidence.

Received pulse width variance

What conditions give an advantage to a shorter transmit pulse?

Case 1:
Airplane
10 km altitude
1 ns transmit pulse
5 m spot on the ground
0.5 m surface roughness

Surface slope (degrees)	Received pulse variance (ns)
0	0.19
1	0.19
2	0.20
3	0.21
4	0.22
5	0.24
6	0.26
7	0.28
8	0.30
9	0.33
10	0.36

Case 2:
Spacecraft
400 km altitude
1 ns transmit pulse
20 m spot on the ground
0.5 m surface roughness

Surface slope (degrees)	Received pulse variance (ns)
0	1.07
1	1.20
2	1.52
3	1.93
4	2.40
5	2.90
6	3.41
7	3.94
8	4.48
9	5.03
10	5.59

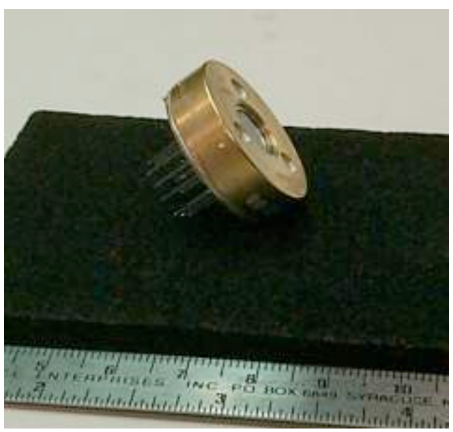
Case 3:
Spacecraft
400 km altitude
1 ns transmit pulse
20 m spot on the ground
0.1 m surface roughness

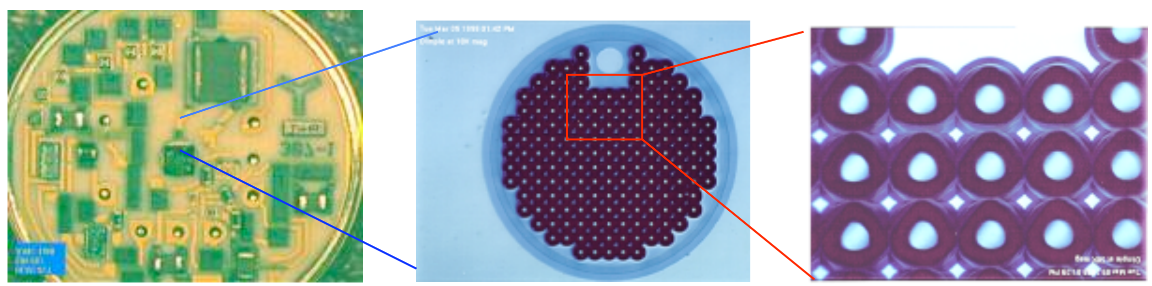
Surface slope (degrees)	Received pulse variance (ns)
0	0.22
1	0.58
2	1.09
3	1.62
4	2.16
5	2.70
6	3.24
7	3.79
8	4.35
9	4.92
10	5.49

Near-Infrared Enhanced (Perkin-ELMER)

Si APD optical receiver

- Near IR enhanced Si APD, preamp, and bias regulator hybrid in a 1” TO-8 package by PerkinElmer Optoelelctronics Canada;
- Successful used in the laser altimeters in Clementine, NEAR, Mars Observer, ICESat, MESSENGER and LRO missions;
- The preamplifier was upgraded with a wide dynamic range and low distortion transimpedance amplifier during the ICESat development;





Near-IR Enhanced (Perkin-Elmer)

Si APD optical receiver Performance

- Quantum efficiency: 40% (0.34 A/W) @1064 nm, 20°C (~50% at 65°C)
- Active area diameter: 700 µm FWHM (800 µm mask)
- Gain: 60-120
- Excess noise factor <3
- Bulk dark current: <50 pA
- Bandwidth: 140 MHz
- Radiation damage: No degradation after $10^{10}/cm^2$ protons (1-100 MeV)
- Responsivity: ~300kV/W
- Preamplifier noise: <1.5 $pA/Hz^{1/2}$
- Noise equivalent power (NEP): 30 – 40 $fW/Hz^{1/2}$, dark
- Linear dynamic range: > 20dB in input optical signal
- Power dissipation: < 0.2 Watts
- Operating temperature range: 0 to 40 deg C
- Lifetime: >10 years in space (vacuum)

Noise Equivalent Power (NEP) Analysis

- APD + TIA Amp NEP

$$NEP = \frac{1}{Rsp}\left[2qI_d F + \frac{\alpha^2}{M^2}\right]^{1/2}$$

$$F = kM + (2 - \frac{1}{M})(1 - k)$$

R_{sp} (=QE*q) is the APD unity gain responsivity

M is the APD optical gain

F is the APD excess noise factor

k is the ratio of the hole and electron ionization coefficients

α is the TIA noise current density

- Critical parameters to reduce NEP
  - Low ionization coefficient ratio, k
  - Low TIA noise α
  - High quantum efficiency
  - Optimize gain (M)

METHOD

Engineer the material (I2E)

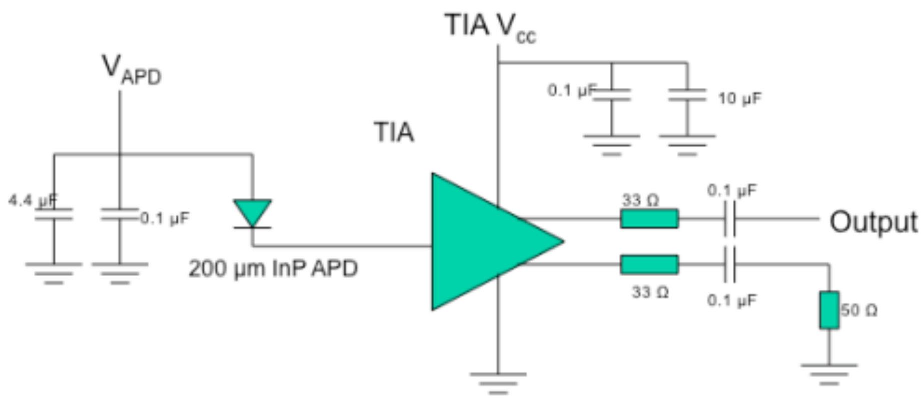
Electronics design

Choice of absorber material

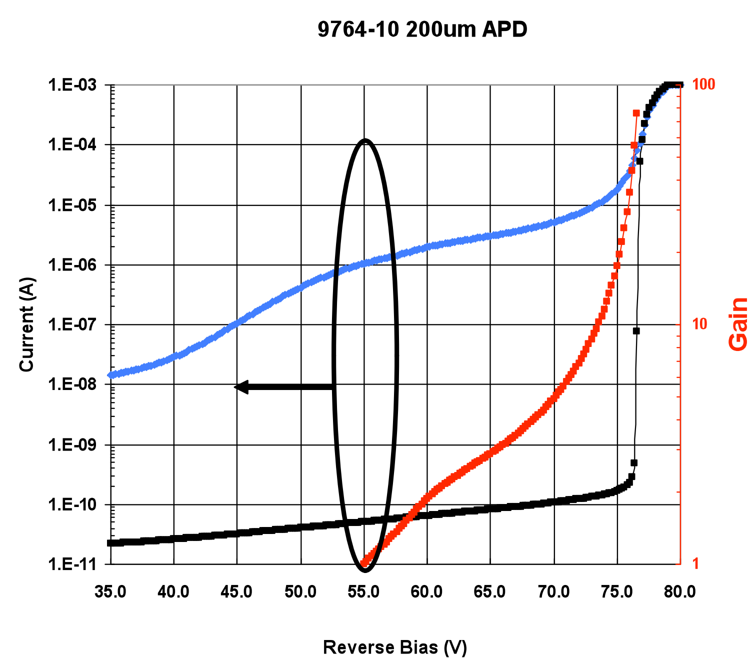
Engineer the material (I2E)

Gen. 1 Photoreceiver Design

- 200 µm InP APD – “off-the-shelf” material
- Low noise TIA , SA5211 1.8 pA/Hz$^{1/2}$
- An integrated TEC cooler and a AD590 temperature sensor chip

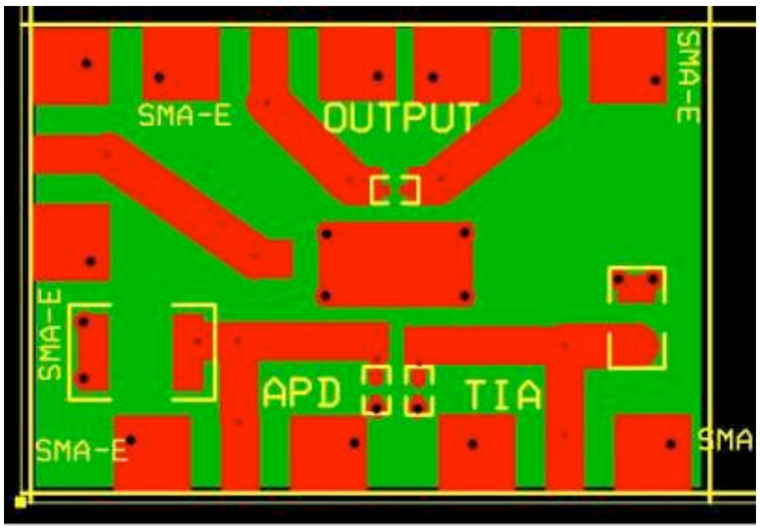


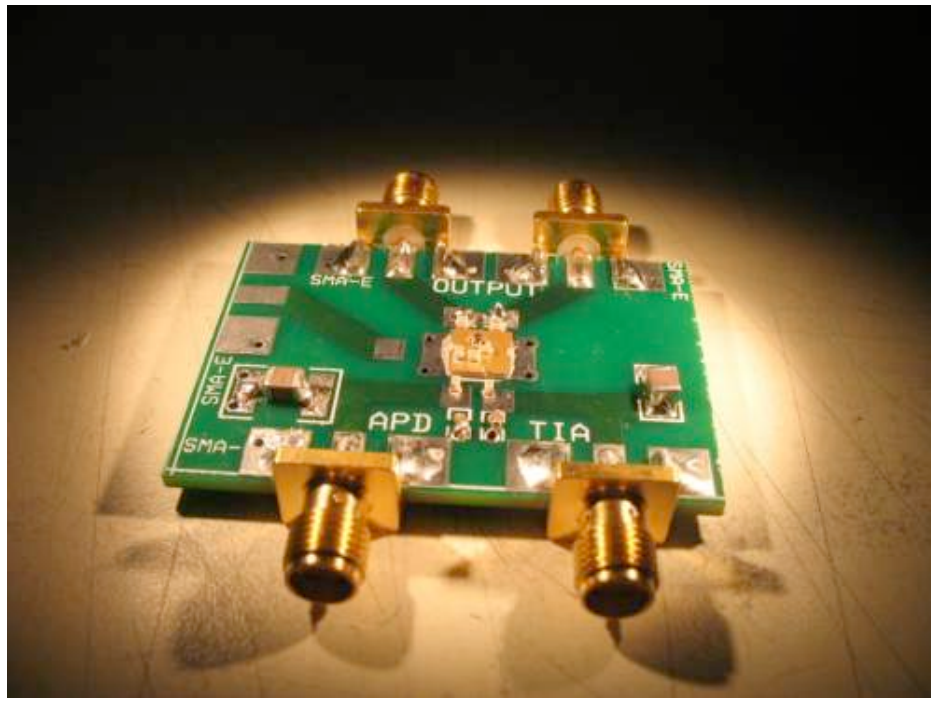
Receiver I-V data



Photoreceiver

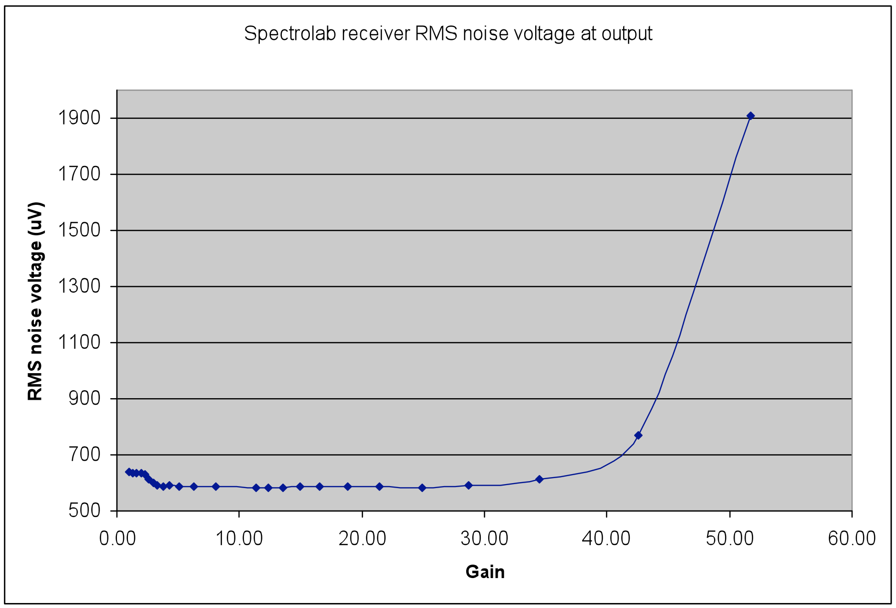
Photoreceiver = APD +Transimpedance amplifier



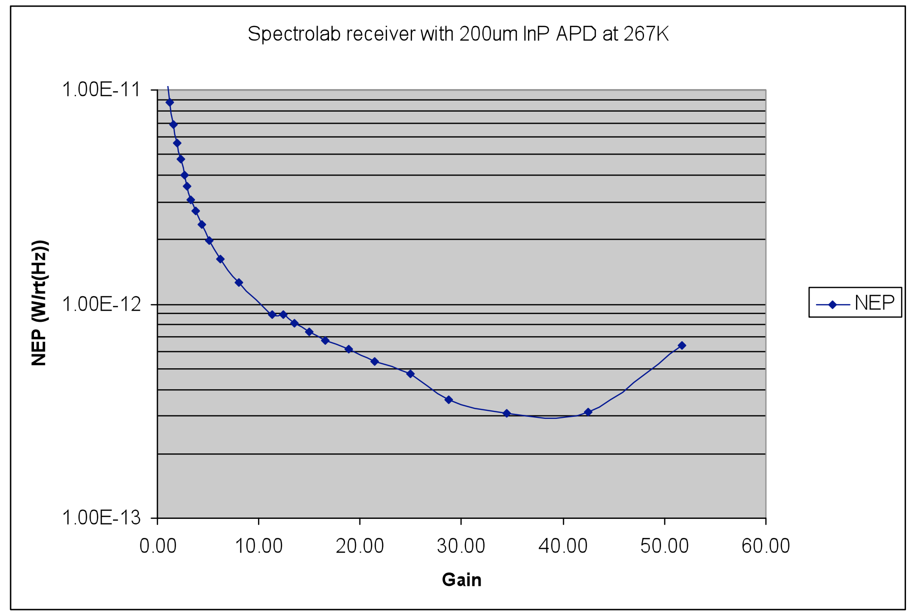


Gen. 1 Photoreceiver NEP Data

RMS Voltage Data



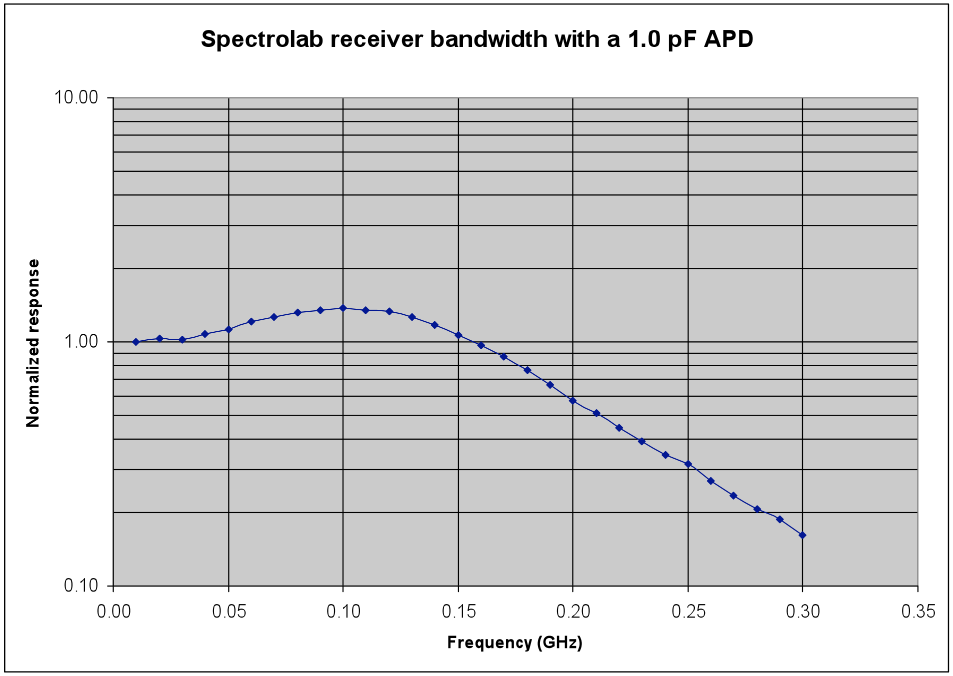
NEP Data

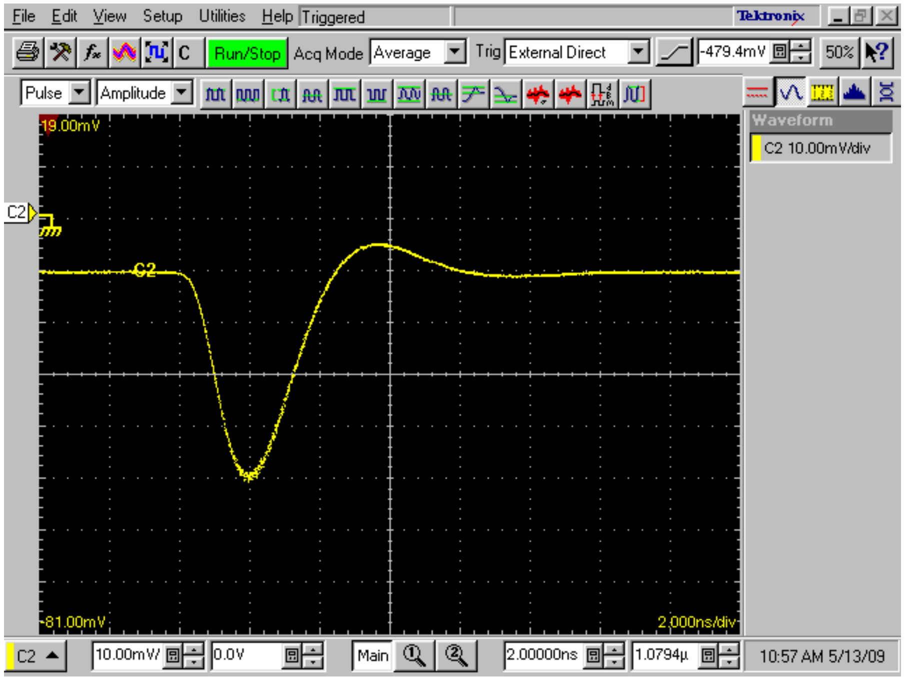


- **NEP < 300 fw/Hz$^{1/2}$ was achieved**

Gen. 1 Receiver Bandwidth

Receiver response to a 100ps 1.06μm laser pulse.





- **Achieved bandwidth of 180 MHz**

Performance metrics

Parameter	Performance	Unit	Approach
Wavelength	1.06	µm	Device
NEP	300	fW/$\sqrt{\text{Hz}}$	Device, circuit
Bandwidth	>1	GHz	Device, circuit
Quantum Efficiency	>75	%	Device
k_{eff}	<0.15	-	Device
Fill Factor	>70	%	Microlens
Number of channels	16		APD array

Gen-2 Receiver Sensitivity Improvements

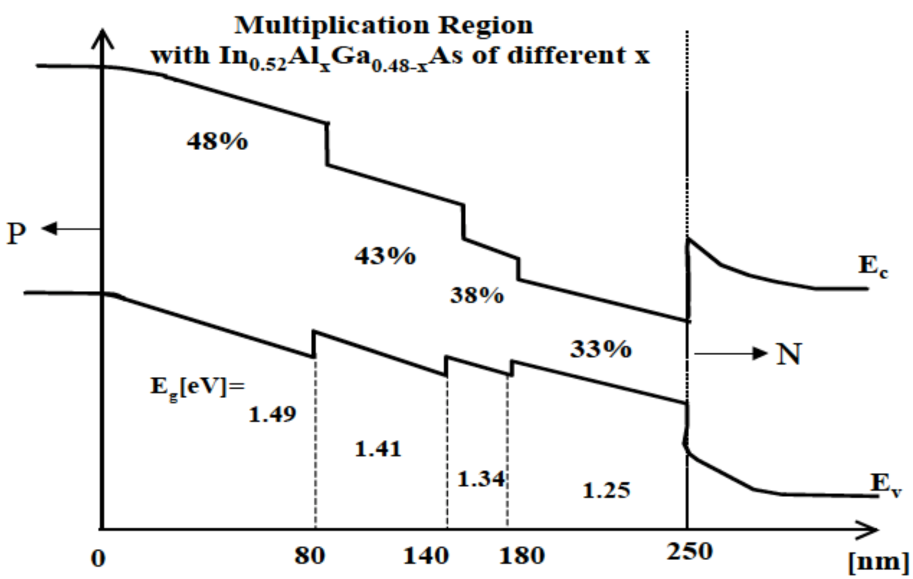
Goal: 300 fW/Hz$^{1/2}$ @ bandwidth of 1GHz

- Quantum efficiency
  - Gen. 1 InP APD has 64% quantum efficiency
  - 75% QE will reduce NEP by 17%.
- Low noise TIAs
  - Select best low noise TIAs in die form with less than 6pA/Hz$^{1/2}$ input referred noise current.
- Reduce excess noise in APD
  - InAlAs has a k value ~0.22
  - Engineer a material (I^{2}E APD design) with reduced $k_{eff} \leq 0.15$

I^2E APD Fundamentals

- APDs have high internal gain and associate excess noise
- k factor is a material parameter for bulk material

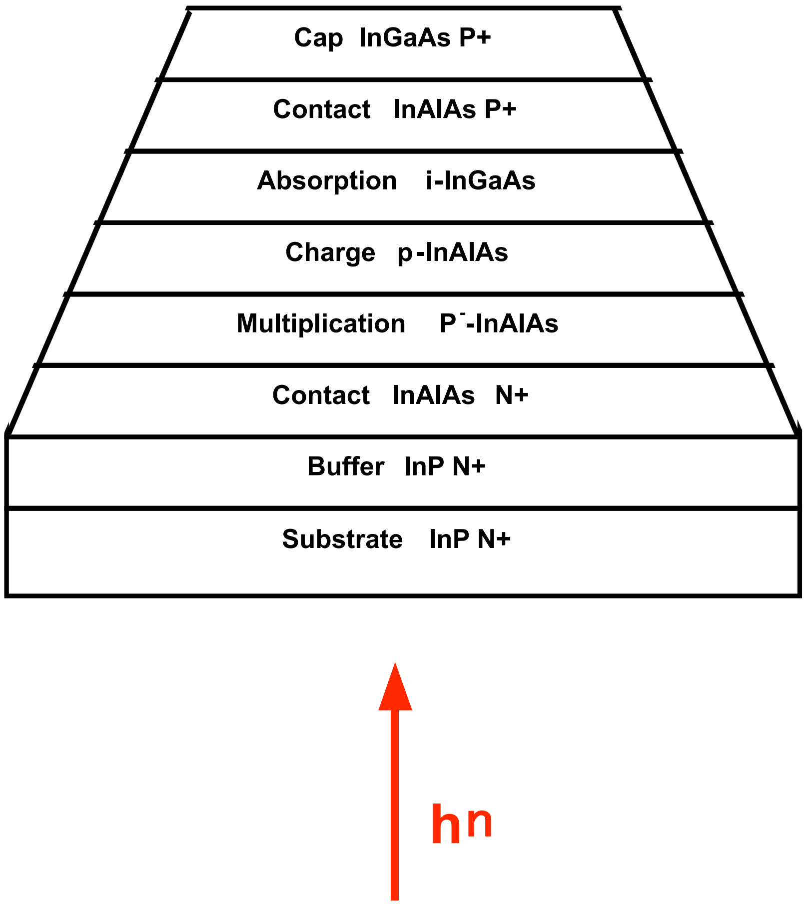
I^2E= Impact Ionization Engineering

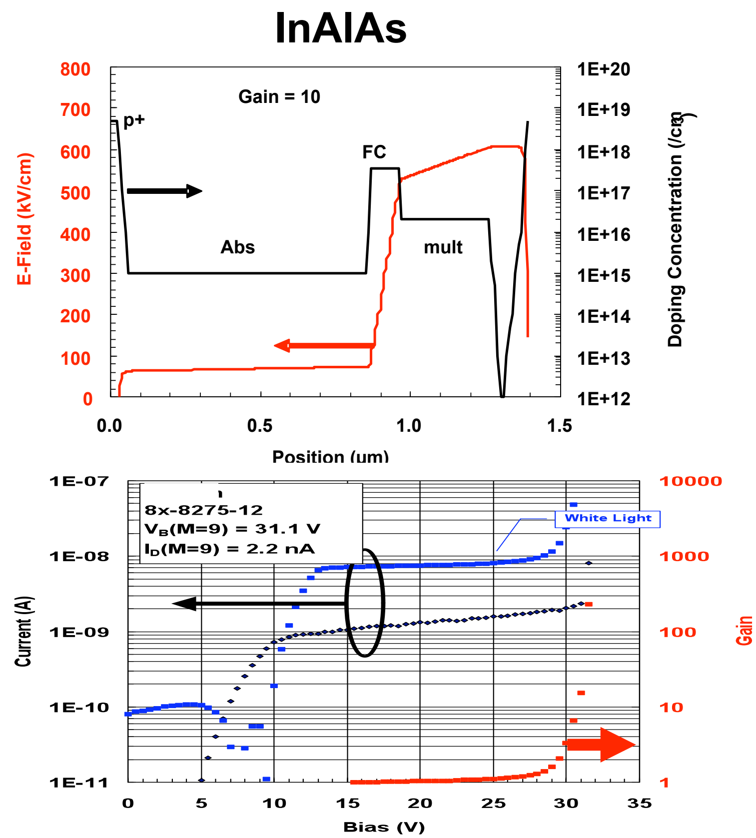


I^2E is an approach to combine materials with different impact ionization threshold energies in the multiplication region. In the I^2E structure, the avalanche events are more deterministic which result in a low effective k-factor (i.e lower excess noise). A lower bandgap material typically has a lower ionization energy threshold.

Graph from S. Wang, et. al., IEEE Photonics Technology Letters, Vol.14, No. 12, pg1722, 2002

Spectrolab InAlAs APD





k_{eff}=0.22

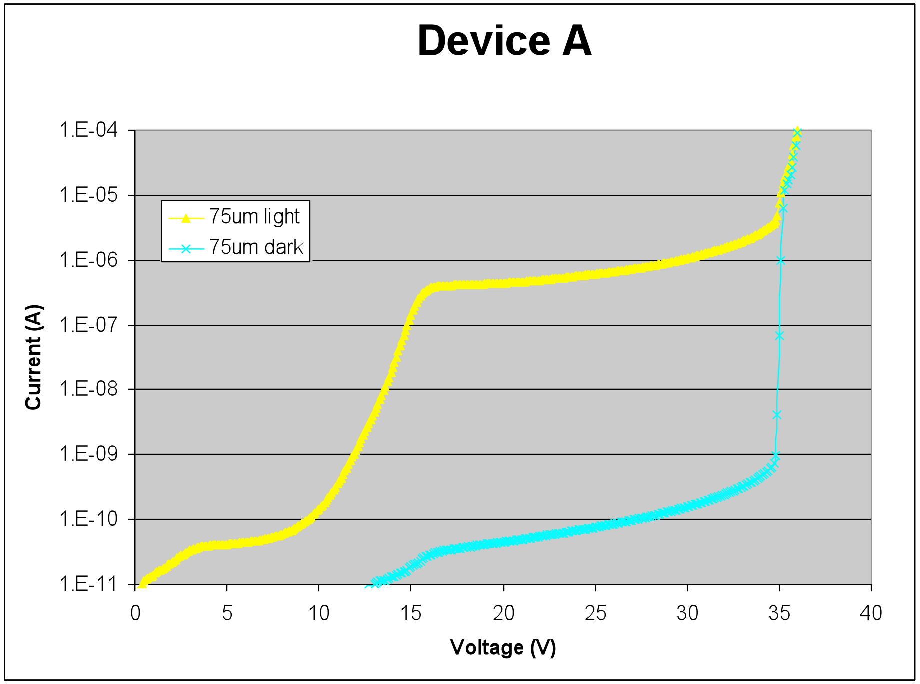
InAlAs APD shows k_{eff} = 0.22

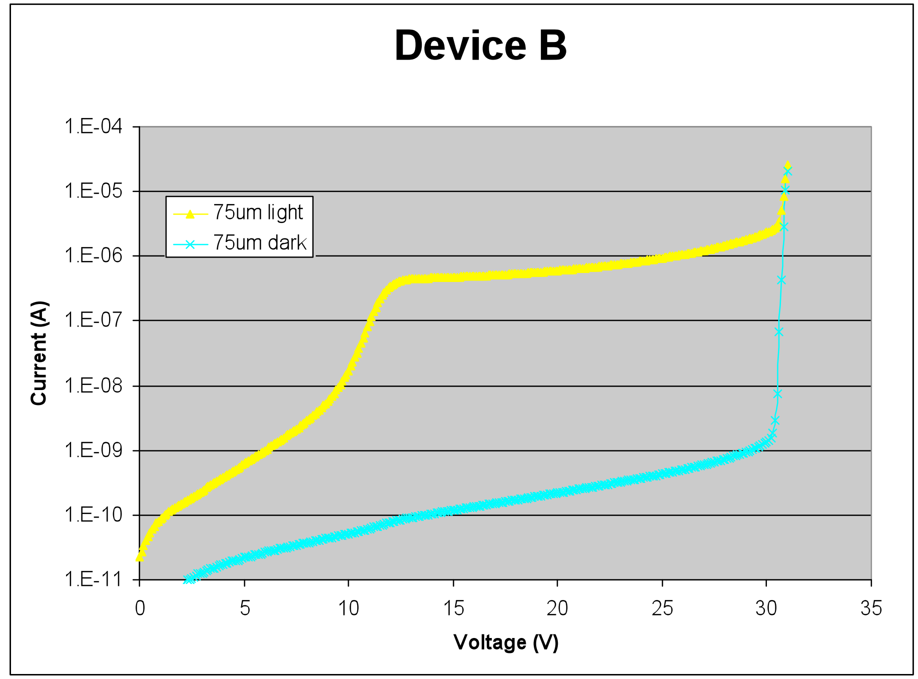
Spectrolab I^{2}E APD Design

p+ InGaAs Cap layer, 50nm
p+ InAlAs, 300nm
i-InGaAlAs Absorber 1200nm Eg~1.05 eV
p+, InAlAs Charge layer
I^{2}E Multiplier
n+ InAlAs Buffer
n+ InP Substrate

- InGaAlAs layer with bandgap of 1.2 eV is used as a multiplier

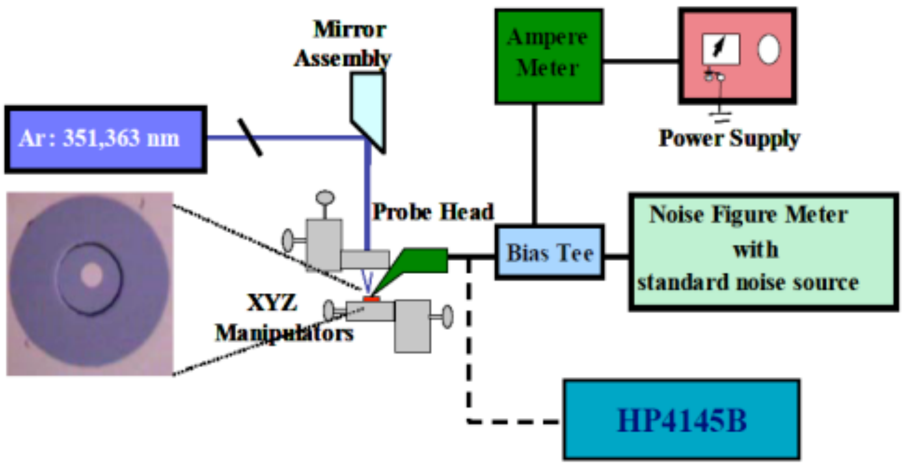
I²E Device I-V Data





- **Show very low dark current before breakdown.**

Excess Noise Measurement



$$S = 2eI_{unity} M^2 F(M) R(\omega)$$

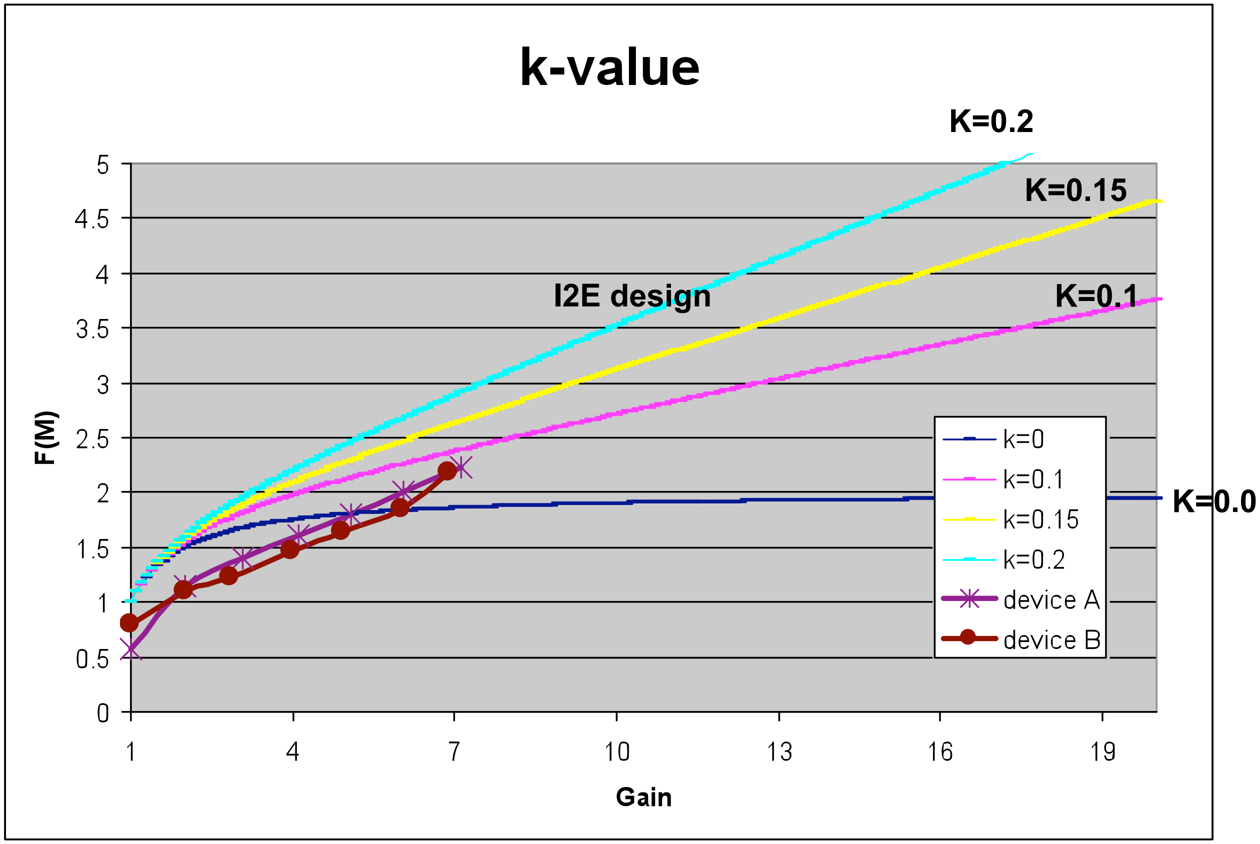
Testing procedure:
(a) At unity gain, measure S vs. I_{unity} to fit the 2eR(w).

(b) Measure S vs. M to get F(M).

UV laser is absorbed near the surface p+ contact layer.
Electrons are diffused into the multiplier, thus pure electron injection is realized.

[*] Setup graph is from Dr. Shuling Wang's Ph. D. dissertation(2002).

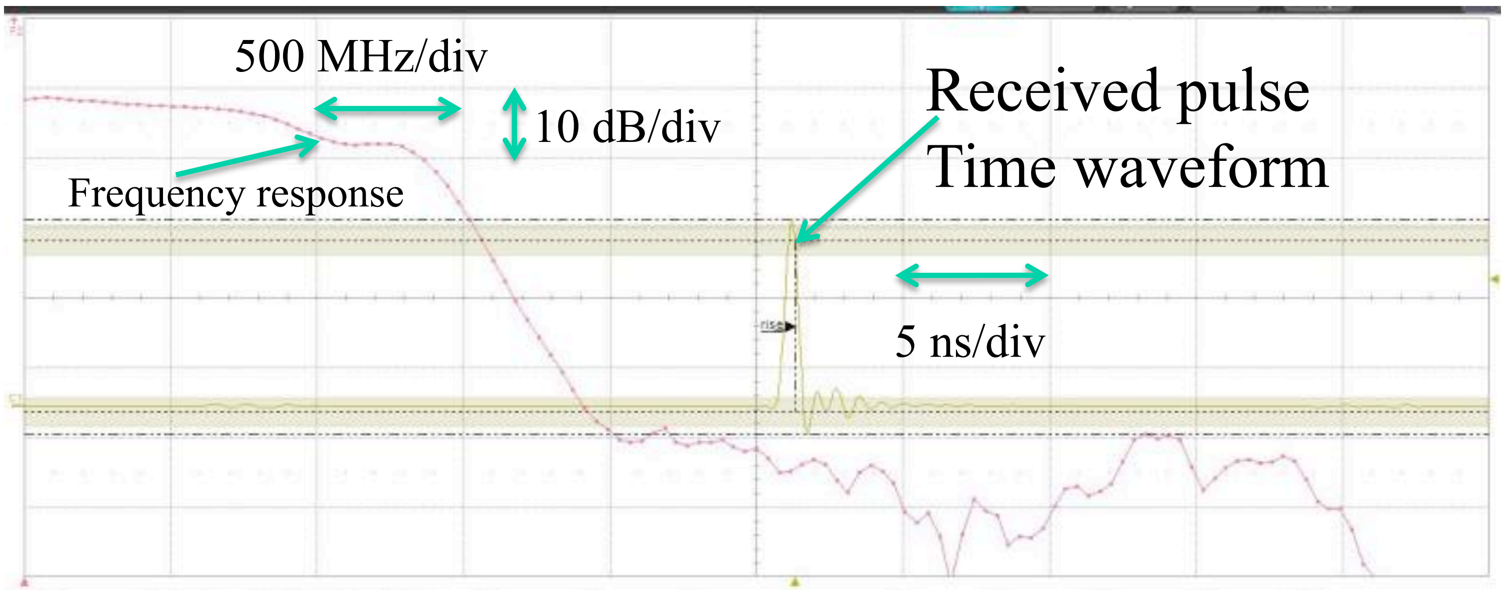
Excess Noise Results



- Both device A and B show k value less than 0.1
- k≤0.15 is feasible at high gain (15~30) for future I^2E

I2E APD (1st run) Pulse/Frequency Response

Waveforms are captured with average of 1024

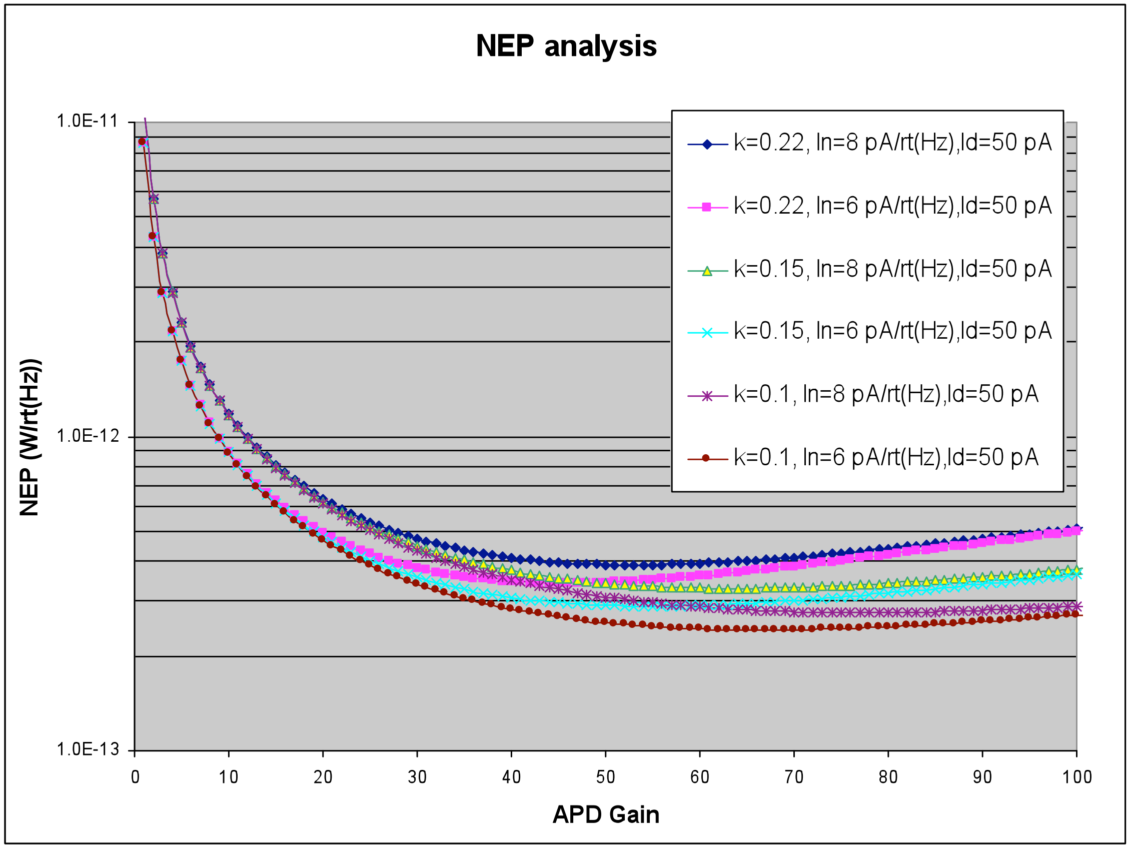


The detector BW is at least 1.5 GHz

Impulse response
Source=PicoQuant Pulse Laser
Laser Input Pulse = 98ps FWHM
Gaussian

BW is limited by the pre-amp
ZFL1000 (1 GHz) and HP8447 (1.3 GHz)
Bias is set to 34.4V
APD Current is measured 0.435mA

Gen. 2 Photoreceiver – NEP Analysis



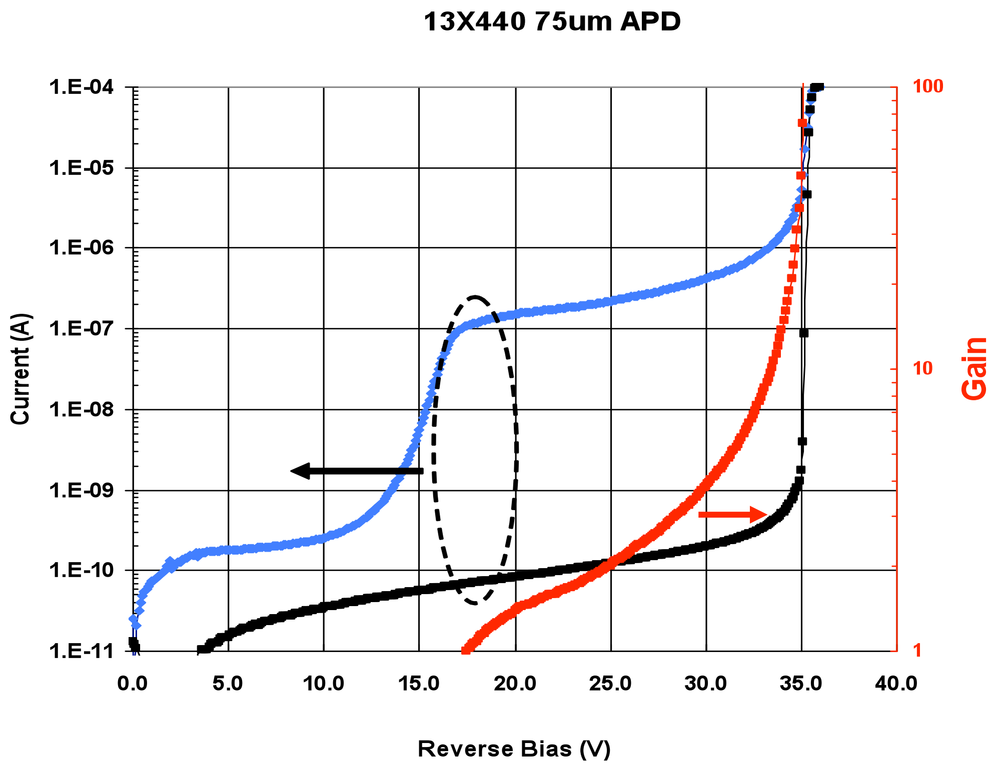
- **NEP less than 300 fW/Hz$^{1/2}$ over 1GHz bandwidth can be achieved using I^{2}E devices**

Recent results – June 2010

- From the first run (late 2009), the I^2E APDs showed low excess noise of k~0.1 but device gain was limited <7.
- In 2010, Spectrolab re -grew the same I^2E APD structure in a new reactor and optimized the growth conditions to increase the gain over >10. **A gain over 50 was achieved** and we assume the same low excess noise since the structure is same. We will re-measure the k-value soon.
- We also designed and built 1x16 APD array and investigated the uniformity. We observed very good uniformity.
- Designed and developed 2nd Gen I^2E APDs to achieve low capacitance. We observed 50% reduction in capacitance.

I^{2}E low excess noise APDs

- Room temperature measurement.
- 200 micron devices
- The photocurrent was measured with APDs illuminated with 1.06 um laser.

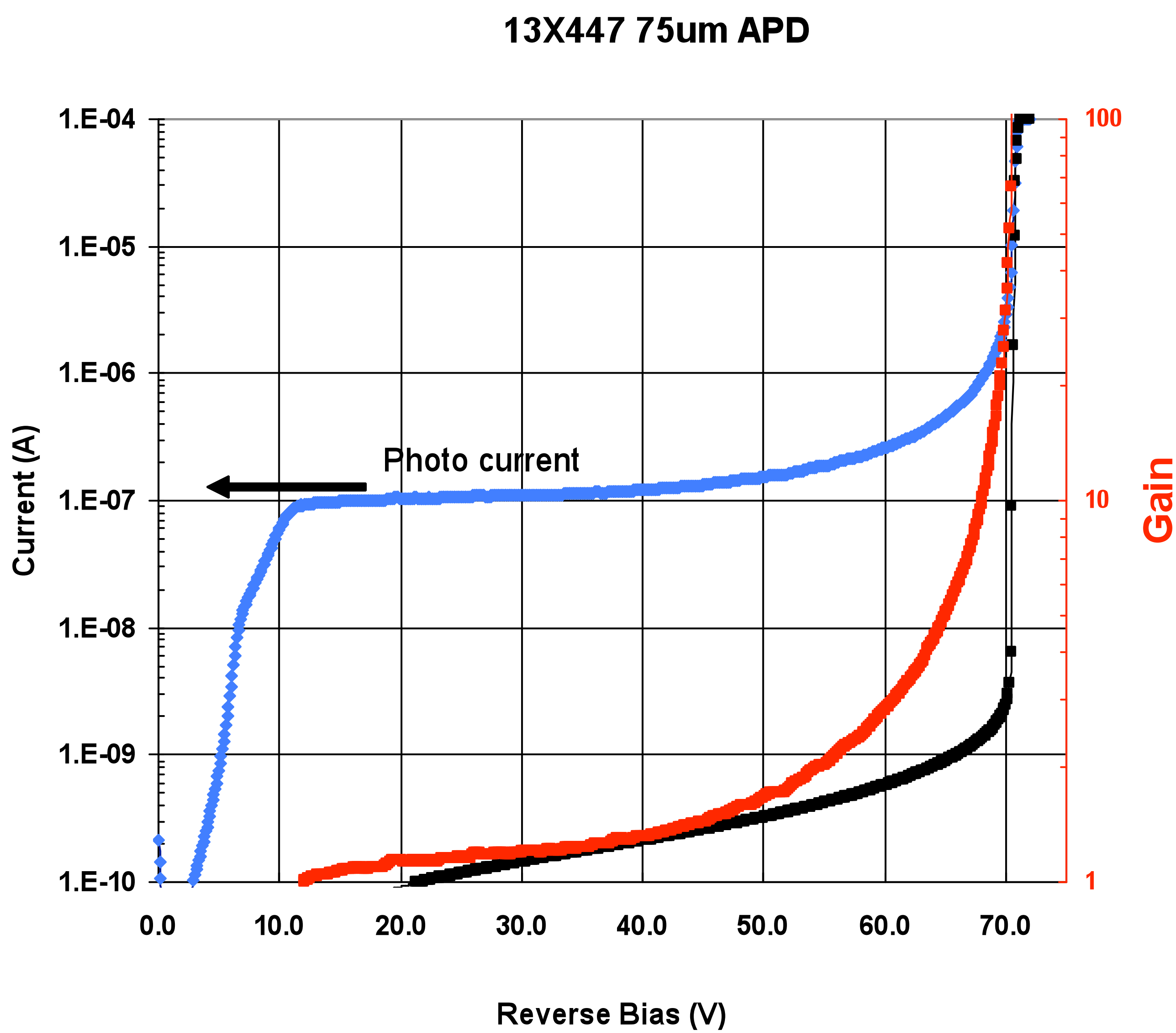


- Improved the gain in our I^{2}E low excess noise APDs

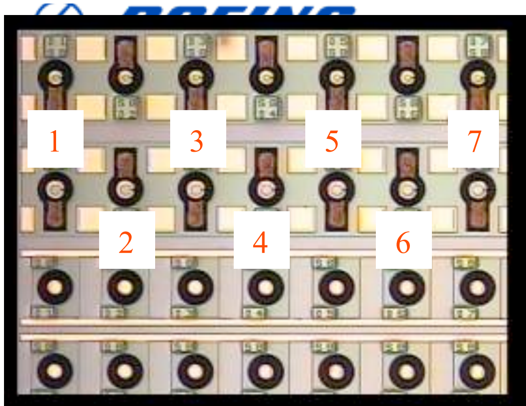
2nd Gen I^2E APDs

- At working gain, the capacitance of Ist generation I^2E APDs is 0.62 pF 75 µm devices
- The capacitance of 2nd Gen I2E APDs is 0.3 pF for 75 µm devices, a 50% reduction in capacitance
- Low capacitance will reduce receiver noise

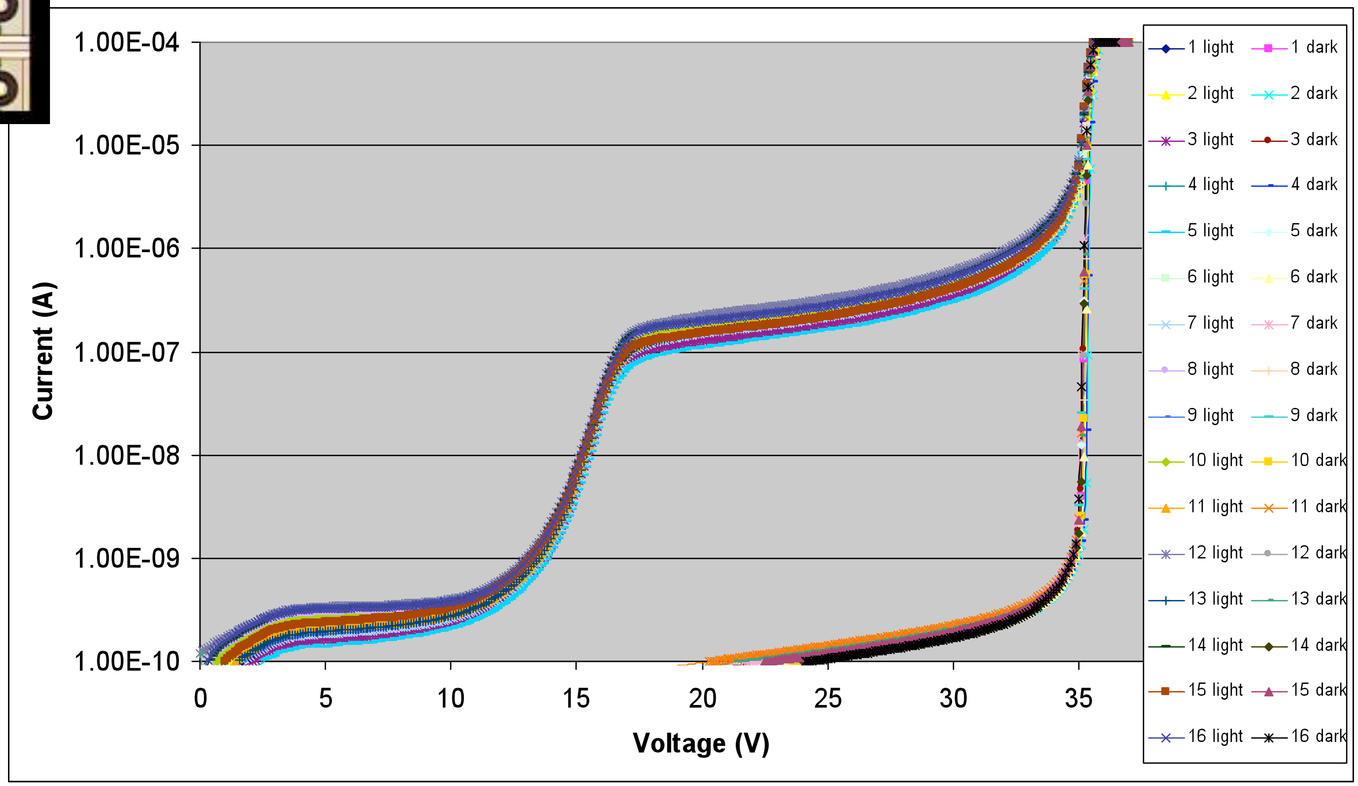
2nd Gen I^{2}E APD IV



1X16 I^2E APD array



- 1x16 I^2E APD array with a pitch of 250 microns.
- Photo current is under 1.06 um laser illumination.
- Breakdown voltages are in a range of 0.2 volt.



- Demonstrated good array uniformity

Summary

- Full-waveform processing lidar receivers provide surface topography, tree canopy and atmospheric data.
- Short pulsed lasers (1 ns) and high-bandwidth (1 GHz) photoreceivers provide improved data:
  - ♦ for airborne lidars
  - ♦ for spaceborne lidars over regions with low surface slope and low surface profile variation
- Demonstrated NEP<300fw/Hz$^{1/2}$ photoreceiver using InP APD
- Developed InAlAs based I^{2}E APDs with > 1 GHz bandwidth.
- Demonstrated low excess noise APDs, k_{eff}<0.1
- Demonstrated gain>50.
- Developing Gen. 2 receiver with I^{2}E APD devices to achieve NEP less than 300fw/Hz$^{1/2}$ over 1 GHz